Dynamical Climatology

Progress and future developments in modelling the climate system with general circulation models.

by

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PROGRESS AND FUTURE DEVELOPMENTS IN MODELLING THE CLIMATE SYSTEM WITH GENERAL CIRCULATION MODELS

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Introduction

The objective of this paper is to review the present status of climate models as a tool in studies of climate change, and to consider the needs for future developments. Progress in development of general circulation models (GCMs) for use in climate studies is a worldwide effort, with many of the major contributions coming from the USA modelling groups. For purposes of illustration here I have mainly used results from the UK Meteorological Office GCM, and must record my debt to those who did most of the actual work of running the models and extracting the results.

Definition of climate models

Firstly, I must say what is generally meant by a climate model in the GCM context. It contains models of the atmosphere, ocean, sea-ice and land; since the pioneering GFDL models constructed by Smagorinsky, Manabe and Bryan in the 1960s the variables have been generally at least surface pressure, wind, temperature and moisture in the atmosphere, current, temperature and salinity in the ocean and snow, surface temperature and soil moisture on land. There have been increases in resolution and complexity. For example, the present UK Meteorological Office climate model has 11 atmosphere layers and 17 ocean layers with a $2\ ^{1}/_{2}°$ latitude by $3\ ^{3}/_{4}°$ longitude horizontal resolution, and a much more complete representation of the land surface is being incorporated.

Uses of climate models

Let us now consider the uses of climate models. An important area is the investigation of natural, internal variability of the climate system; one example is the irregular 3-5 year time scale tropical Pacific ('El Nino') ocean surface temperature variation. Another major use is for the study of the effects of naturally forced perturbations of climate. These fall into 3 groups (Table 1). Firstly, there are astronomic variations:- in solar output these range from long trends over billions of years to shorter term variations, 22 or 80 year cycles perhaps; then there are the perturbations of the earth's orbit which have been discussed in this symposium by Peltier, and in a union lecture by Berger. Secondly, there are variations in atmospheric composition - in volcanic aerosols as discussed by Sigurdsson in this symposium, trace gases such as the CO_2 variations associated with glacial cycles, and tropospheric aerosols in which variations may arise due to changes in vegetation or surface winds -these may also be associated with glacial cycles. Thirdly, there are changes in surface boundary conditions - those due to continental drift as Barron has discussed in this symposium and those in vegetation, ice caps etc. associated with glacial cycles.

Turning now to man-made perturbations (Table 2) there are again three groups. Firstly, atmospheric composition - study of the effects of increases in trace gases is probably the most important use of climate models and is discussed elsewhere in these symposium proceedings. Secondly, man's tendency to change the land surface, like his effect on CO_2, imposes on climatologists the responsibility of assessing the effects of such changes (see Nicholson, this symposium). Thirdly, there are changes in water management - diversion of rivers, construction of reservoirs, drainage of wet lands. I have indicated under each item in Table 2, the processes in a climate model affected by the changes. This is relevant to the next topic -what requirements these uses of climate models place on the models. Table 3 shows these for some applications. There are two types. Firstly, to be able to study the effects of these changes it is necessary to be able to represent the perturbation. Thus, we cannot study the effects of aerosols on precipitation formation without a sufficiently realistic representation of cloud microphysics, in which the effect of aerosol size distribution and other factors is taken into account. Deforestation cannot be properly simulated if the model's hydrology parametrization cannot represent the effects of a change from forest to, say, pasture.

The other requirement is that the effects be properly described. Here the need is not only for adequate model diagnostics but also sufficiently realistic simulations of the required model parameters. Just taking one example, agriculture (Table 3), you see that the list is quite extensive. Note also how what is needed is nearly always surface data - not upper winds and temperatures; indeed, of the non-surface variables, only clouds will occur frequently in the list of requirements and then mainly because of the impact on surface radiation. Also, it is often frequency distributions and interannual variability that are required, not means; and the frequency distributions may be complex - e.g., occurrence of low temperatures together with strong winds for ship icing. However, today I shall restrict my discussion to time averaged results.

Some results

Let me now take you fairly quickly through some recent results, most of which provide some illustration of progress in modelling. One quite instructive model field is that of sea level pressure. The two top frames in Figure 1 show a 4 year observed northern winter normal - very like longer periods - and an 8 year mean from our model as it was around 1984. Note the excessive westerly flow, a problem common to relatively high resolution models at that time. This was not a problem in the Southern Hemisphere - not shown here (see Slingo and Pearson [1987]) but the simulation there is very good with mean sub-Antarctic pressures of about 980 mb and realistic sub-tropical ridges. This suggests a problem with orography, as this is relatively unimportant in the Southern Hemisphere. The first solution proposed was to enhance the orography (e.g. Hills [1979]) in order to represent the barrier effects of mountains better. Later, the envelope orography technique [Wallace et al, 1983] was tested [Slingo and Pearson, 1987]. This worked quite well in winter but the northern summer circulation was degraded, probably because the elevated heat sources were too elevated.

The second solution was to incorporate a representation of the vertical transfer of momentum by gravity waves, in other words gravity wave drag [Palmer et al., 1986, Slingo and Pearson, 1987]. This also had a dramatic

effect (Figure 1c) on the simulation as easterly stress or momentum flux convergence, applied at the earth's surface over rough (i.e., mountainous) areas, was transferred to higher levels, where it decelerated the westerly flow. With this change, how realistic are model winds? The results in Figure 2 are for a 4 winter mean from our latest long run of the model. The pattern of zonal mean winds is quite close to observations, though the jets are too strong. Differences greater than 5 m/s are shown in Figure 3 -mostly they are confined to the stratosphere. The other contours here are for temperature errors - mostly these are less than 4 K except in the polar stratospheres. A similar result is obtained in June to August (Figure 4). This stratospheric coolness is not a problem peculiar to our model - all three of the models used for CO_2 experiments reviewed by Schlesinger and Mitchell [1985] suffered from such errors, especially in the Southern Hemisphere. A possible cause is the rather poor resolution of the stratosphere - we have only three layers above 200 mb - in view of the important role of vertical motions in the stratospheric heat balance. However, Mahlman and Umscheid [1984] have errors approaching 10 K in the January of their simulation with a much higher resolution (40 level) model. One might also suspect radiation as a cause. The ICRCCM (Intercomparison of Radiation Codes for Climate Models) organised a valuable comparison of line-by-line models and parametrizations for climate models; Figure 5 compares two line-by-line comparisons of long wave cooling - GFDL and LMD. Though this shows generally good agreement, there are differences. Apart from the coarse resolution, the MO model's differences from the line-by-line calculations are of comparable magnitude; however there is too much cooling from 60 to 370 mb. Note that these schemes omit the water vapour continuum. Though this is a poorly understood area of radiation theory, a better representation would not affect the stratospheric cooling.

Further intercomparison programmes are underway - for boundary and surface fluxes, as discussed by McBean (this symposium). In this context, it is relevant to examine the surface winds which are of such importance for driving an ocean model. Figure 6 shows the zonal mean of the eastward surface stress on the ocean surface, averaged over the year, compared with Hellerman and Rosenstein's estimate from observed data. There are differences, but mostly these probably owe as much to uncertainties in the data and the differences in the stress formulation as to errors in the model winds. An exception is probably near 50-60° S, where the model's peak westerlies are a few degrees too far from the pole, and north of 60° N, where some easterly bias is present.

Rainfall (Figure 7) is important for agriculture over land and over the ocean because of salinity's role in driving ocean currents. This simulation, though not as good in several respects as some of our earlier ones, nevertheless serves to demonstrate that broadly the patterns are realistic. The 'desert' areas with less than 1 mm/day and the rainy areas with more than 5 mm/day are broadly similar in the simulated and observed maps. Features which were worse here than in most of our experiments included several parts of the tropics, for example the excessive rain over South America and northern Australia and the deficient rain over the tropical Atlantic and southern tropical Africa. For many purposes, it is also important to simulate the runoff well - we have recently started to calculate runoff for selected basins, simply summing the runoff of grid boxes within the catchments. One basin we considered was the Mackenzie River which runs through Arctic Canada. The result (Figure 8) was disappointing with too strong a summer snow melt peak and too little the rest of the year. However, the model is not necessarily so wrong in high

latitudes. Another comparison (Figure 9) we made was for the region of Siberia from 60-105° E north of 50° N, which closely approximates the basins of the Ob'Irtysh and Yenisei. Here, the model had nearly 50% too much run off, but the apportionment through the year is close to observed.

An important need in climate change studies, especially those involving CO_2, may be sea level information. To obtain this, it is essential to have an ice sheet model and a prerequisite for that is realistic snow accumulation. This is obviously very dependent on getting precipitation right but other factors are also important, as shown by the ice budget analysis for the North American ice sheet at the last glacial maximum in Manabe and Broccoli [1985]. Their results show the sublimation to be nearly half as large as snowfall. We have calculated snow budget data for Antarctica and compared it to the estimates by Schwerdtfeger [1970] (Figure 10). The broad pattern of a minimum of less than 5 g cm^{-2} yr^{-1} over most of eastern Antarctica, with peak values near the coast of over 40 g cm^{-2} yr^{-1} in places, is simulated quite well. The South Pole apparently has too little - there is a maximum on the south edge of the Ross Ice Shelf, but like much of western Antarctica, magnitudes are too small.

The results discussed so far are from atmosphere models. It is obvious that the simulation of the surface climate from coupled models cannot, except through chance cancellation of errors, be expected to be as good as that for atmospheric GCMs, which use climatologically correct sea surface temperatures (SSTs) and sea ice. So the crucial question is how good are the SST and ice simulations in coupled models - I will discuss only SST, referring to Han et al. [1985]'s useful comparison of annually averaged SST errors. Their maps show rather large areas with errors exceeding 4 K -i.e., greater than the largest observed anomalies - and there is much in common between the simulations which is only partly disguised by the range of up to 2 K in the mean errors. These common features include a warm Antarctic Ocean and eastern southern hemisphere oceans, cool water in the northwestern tropical and sub-tropical oceans, warm north Pacific and northwest Atlantic and cool northeast Atlantic. Most of these errors are, I think, not well understood.

Future

Now I want to touch on a few of the many challenges and problems in modelling climate. Table 4 indicates some likely future developments and problems. One of the most important may be ocean eddies - how important for modelling climate is it to get the eddy transports right? And if they are crucial, how can they be simulated without the enormous increase in computing power needed to represent the eddies explicitly - about 3 orders of magnitude with a 10 km mesh instead of a 300 km one? Possibly they can be parametrized -though the methods have not yet been developed. Table 4 also lists some other ocean modelling problems. Firstly initialization: can WOCE provide a suitable data set for, say, initializing the ocean for 100 year CO_2 runs starting in 1995? Secondly, the tropical oceans - do we need to simulate the delicate balance illustrated in real data by the existence of two quasi-steady states in the tropical Pacific? Thirdly, the high latitude oceans - the large and quite rapid variations of North Atlantic circulation, for example around the Younger Dryas period, suggest another delicate balance.

Another major problem area is clouds. As discussed by Schlesinger in this symposium, current GCMs mostly omit any dependence of cloud radiative properties on water or ice content, and so omit a possibly important

negative feedback if, as suggested by Somerville and Remer [1984], albedo tends to increase with temperature. The problem is not with calculating the water or ice content. There are ways of doing this already. Figure 11 shows a calculation of zonally averaged cloud water content for September (R N B Smith, personal communication) with a scheme developed from that of Sundqvist's. It verifies quite well against SMMR data for ocean only, except that the falloff towards high latitudes is too early and too fast compared with the satellite data. However, the water path must still be interpreted in terms of cloud radiative properties. This is not straightforward as Figure 12 (W. Ingram, personal communication), showing several proposed relationships between reflectivity and water content, illustrates. Clearly, estimates of drop size effective radii are needed if uncertainties of up to 10 per cent in albedo are to be avoided.

Land surface parametrizations are becoming much more comprehensive. However, the land surface poses some other interesting problems. Let me illustrate these with the simulation of the climate 9000 years ago when the solar radiation at the top of the atmosphere differed from that of the present day by about as much as it has in the last few tens of thousands of years. There were increases of 30-40 Wm^{-2} over parts of the Northern Hemisphere in summer. This was due mainly to the different time of perihelion - in July compared to January at present. Kutzbach and Guetter [1986] simulated the effects of this in the NCAR CCM and obtained precipitation increases in summer across the Sahara and Arabia, as well as southern Asia. These results are consistent with paleoclimatic data indicating high lake levels over the Saharan region at about 9000-6500 years BP. Mitchell et al. [1988] used the UK Meteorological Office model with a 50 m slab mixed layer ocean to simulate the effects, but although rainfall increased over southern Asia and eastern Africa, they obtained little change, even some decreases over the central and western Sahara. The explanation of this difference between the models was traced to the formulations in evaporation: the NCAR model used one quarter of the potential evaporation, however little soil moisture there was, so that evaporation was able to respond to increases of radiation and allow the model to develop a moist climate. In the Meteorological Office scheme, any increase in evaporation had to be met from soil moisture and, as there usually is little over the model Sahara, no evaporation increase occurred. However, if the albedo was decreased to values typical of grassland, precipitation did increase fairly widely as a result of the Charney albedo feedback mechanism. Now, such a vegetation change could occur gradually as a result of a slow increase in moisture availability but, without interactive vegetation, the climate model cannot represent it.

This brings me to my final point, that we must expect to expand climate models. Such an expansion to include modelling of vegetation appears necessary. Eagleson's talk in this symposium suggests possible directions for such a development. However, note that the role of man in determining vegetation implies a need for models of society. The same applies to other expansions - not perhaps to ice sheet models, but certainly carbon cycle models (see Bolin's and Toggweiler's papers), and ozone chemistry models needed for experiments exploring the effects of chlorofluorocarbons.

Summary and Conclusions

(1) There are many possible uses for climate models. These include the study of the climatic effects of natural and manmade perturbations of the forcing. Such applications mostly require diagnostic output relevant to climate at the surface, rather than higher in the atmosphere.

(2) Model characteristics are obviously determined in part by the requirement for a realistic simulation. However, the need to represent perturbations of the forcing and the nature of the guidance required are also important constraints.

(3) Atmospheric GCMs are generally adequate for climate simulation purposes though developments are needed in the representation of cloud radiative properties and mountains and in the simulation of regional variations. Important problems lie ahead in ocean modelling, at least if eddies need to be resolved, and in the incorporation of vegetation and ice sheet models and the representation of interactions between climate and society.

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TABLE 1. Natural perturbations of climate

(a) Astronomic variations:-

Solar output
(long term trends, oscillations)
Earth's orbit

(b) Atmospheric composition variations

Volcanic stratospheric aerosols
Trace gases, tropospheric aerosols
(glacial cycle variations in vegetation etc)

(c) Surface boundary conditions

Continental drift
Glacial cycles
(icecaps, sea level, lakes, vegetation)

TABLE 2. Manmade perturbations of climate

(a) Atmospheric composition

Trace gases
(fossil fuel, CFCs)
- Radiation
Aerosols
(land use, ocean biota)
- Radiation, cloud physics

(b) Land surface

(deforestation, afforestation,
desertification, irrigation)
- Radiation, turbulence, hydrology

(c) Water management

(river diversions, reservoirs)
- Runoff, salinity, evaporation

TABLE 3. Requirements on climate models

(a) Represent perturbations
e.g. deforestation, trace gas radiation effects.

(b) Describe effects
e.g. Agriculture -
radiation
temperature
soil moisture (precipitation, evaporation)
snow cover, frost
sea level
similarly for:
Fisheries, Water, Power, Transport, Construction, etc.

TABLE 4. Future developments, problems

(a) Ocean: - eddies
Tropical (El Nino)
Extratropical (glacial cycles)

(b) Cloud: - water content -> albedo

(c) Mountains: - elevation
(barrier or heating)
gravity waves

(d) Land surface: - soil, etc datasets

(e) Other possible developments:
vegetation models
ice sheet models.

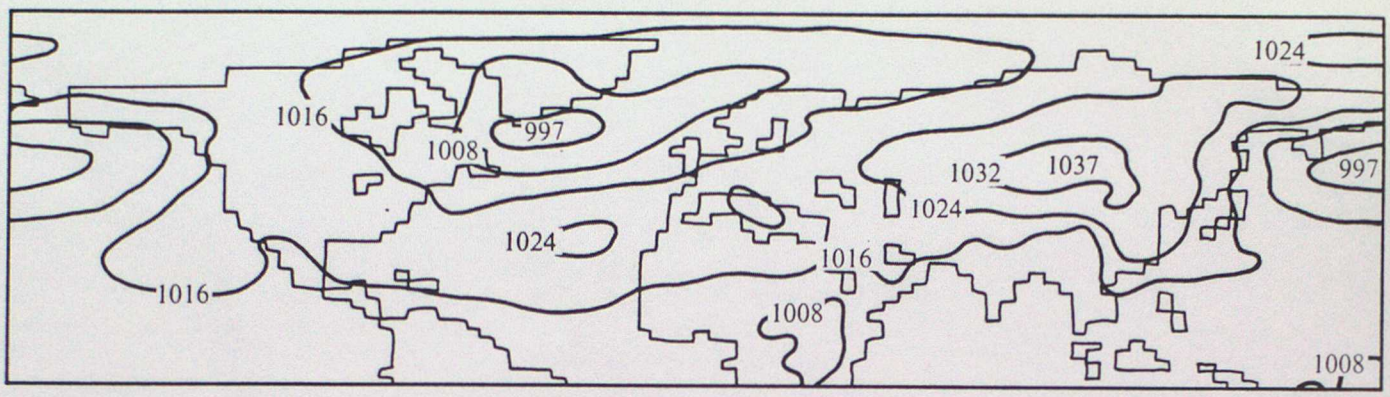


Fig. 1a

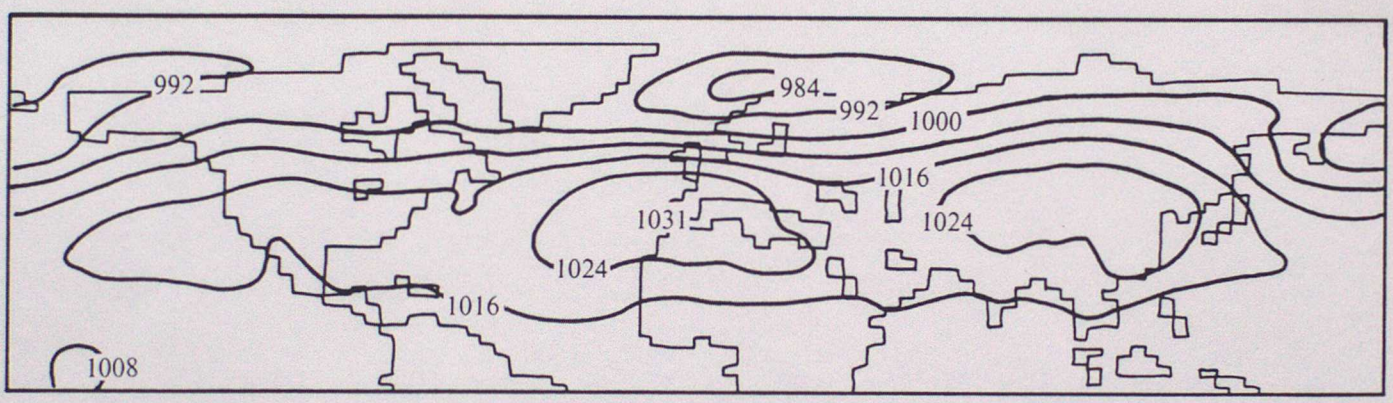


Fig. 1b

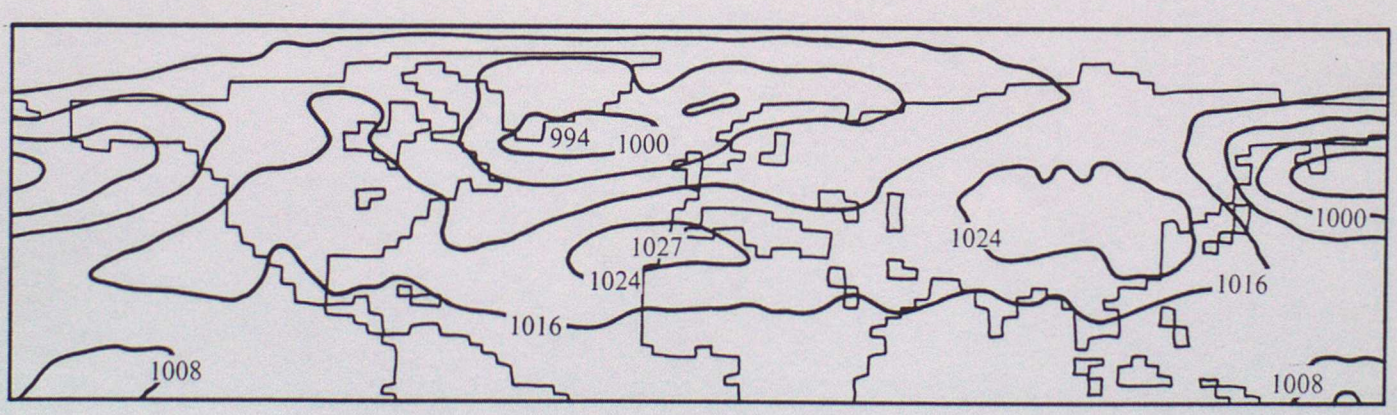


Fig. 1c

Figure 1: December-February sea level pressure: (a) observed, based on Meteorological Office (MO) operational analyses for 1983-86; (b) modelled, average for 8 winters without gravity wave drag; (c) modelled, average for 4 winters with gravity wave drag.

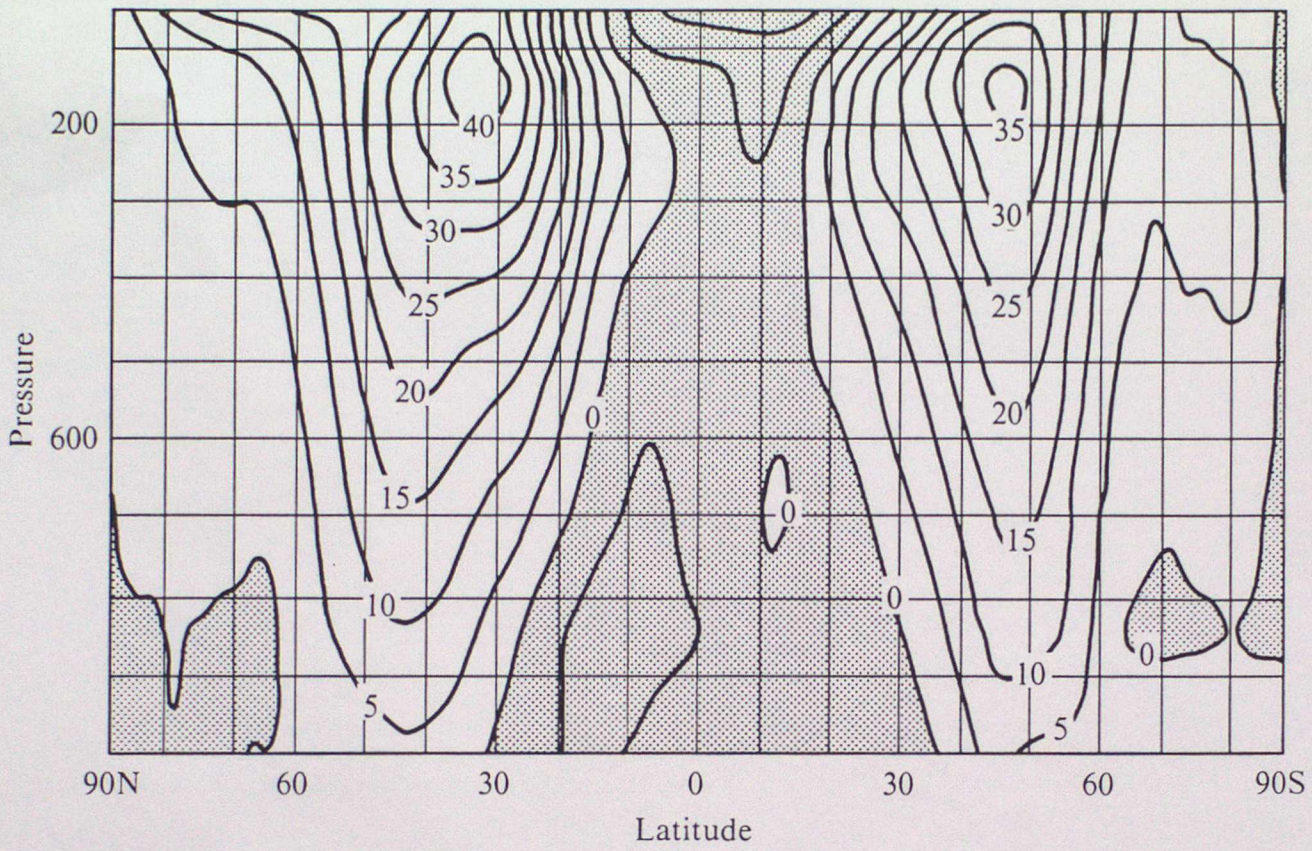


Fig. 2a

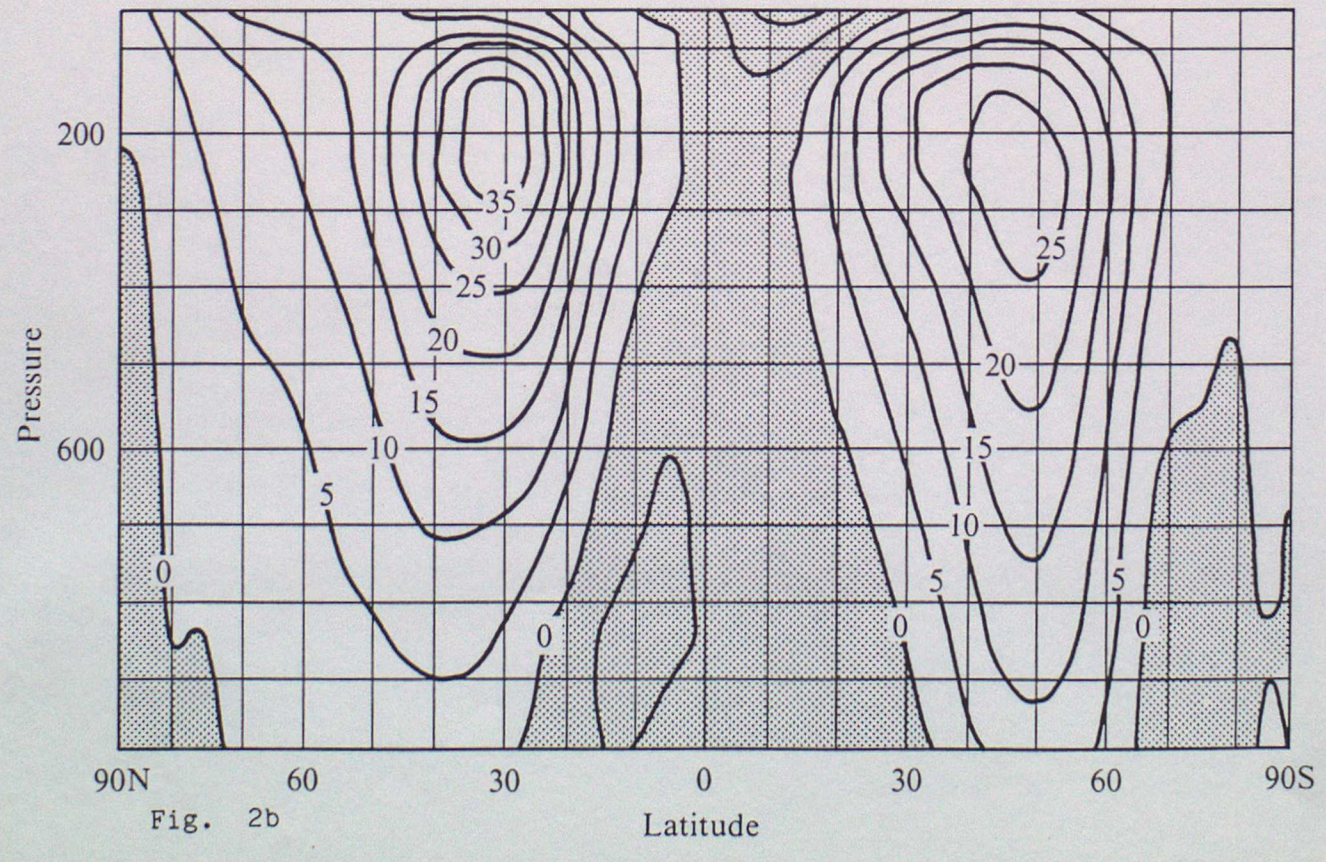


Fig. 2b

Figure 2: December-February zonally averaged zonal winds: (a) modelled 4 year average; (b) observed 3 year mean (1983/4-1985/6). Contour interval 5 m/s; easterlies shaded.

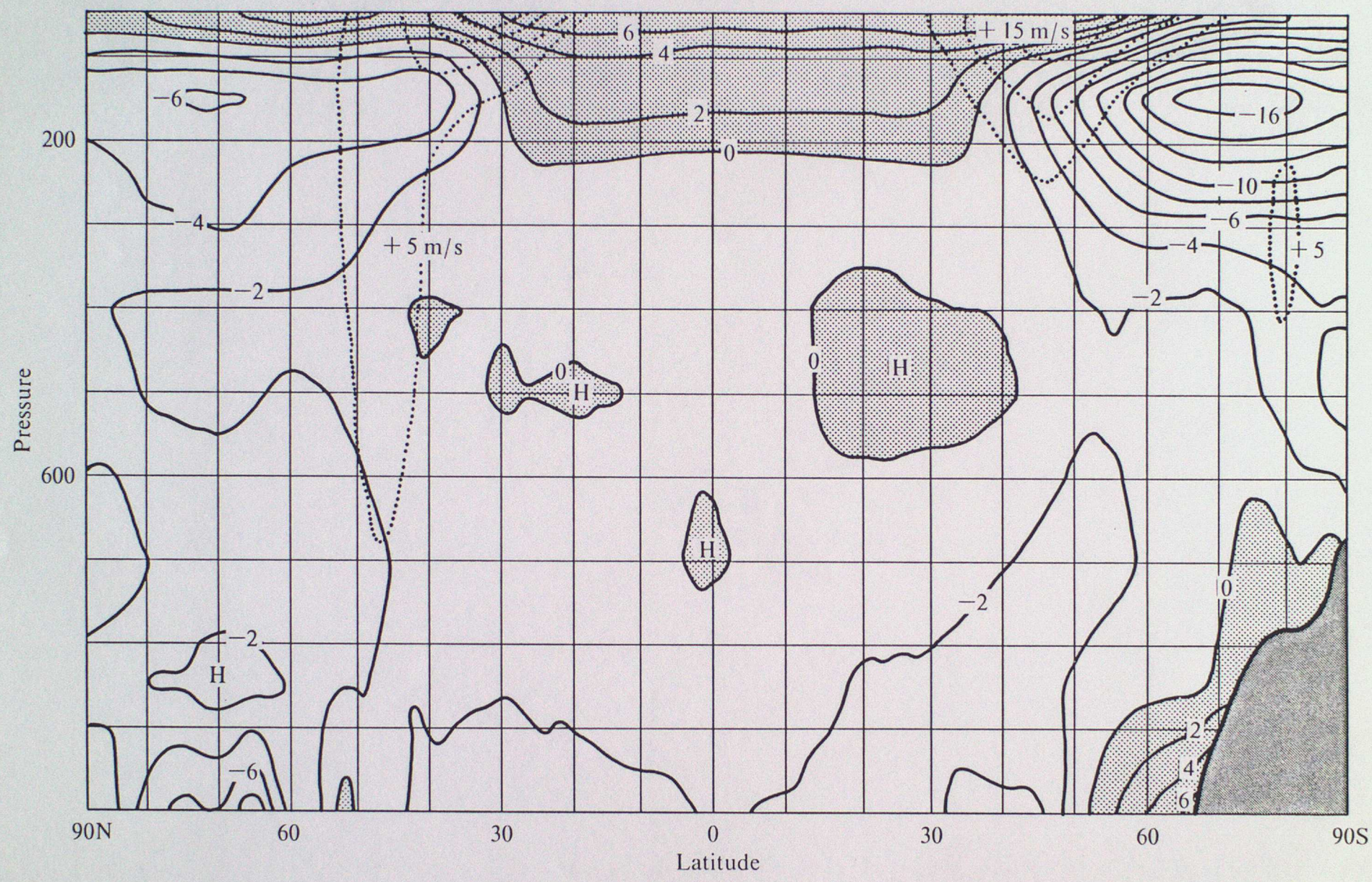


Figure 3: December-February zonally averaged model errors for temperatures (solid) and zonal winds (dashed). Contour interval 2K for temperature, 5 m/s for winds.

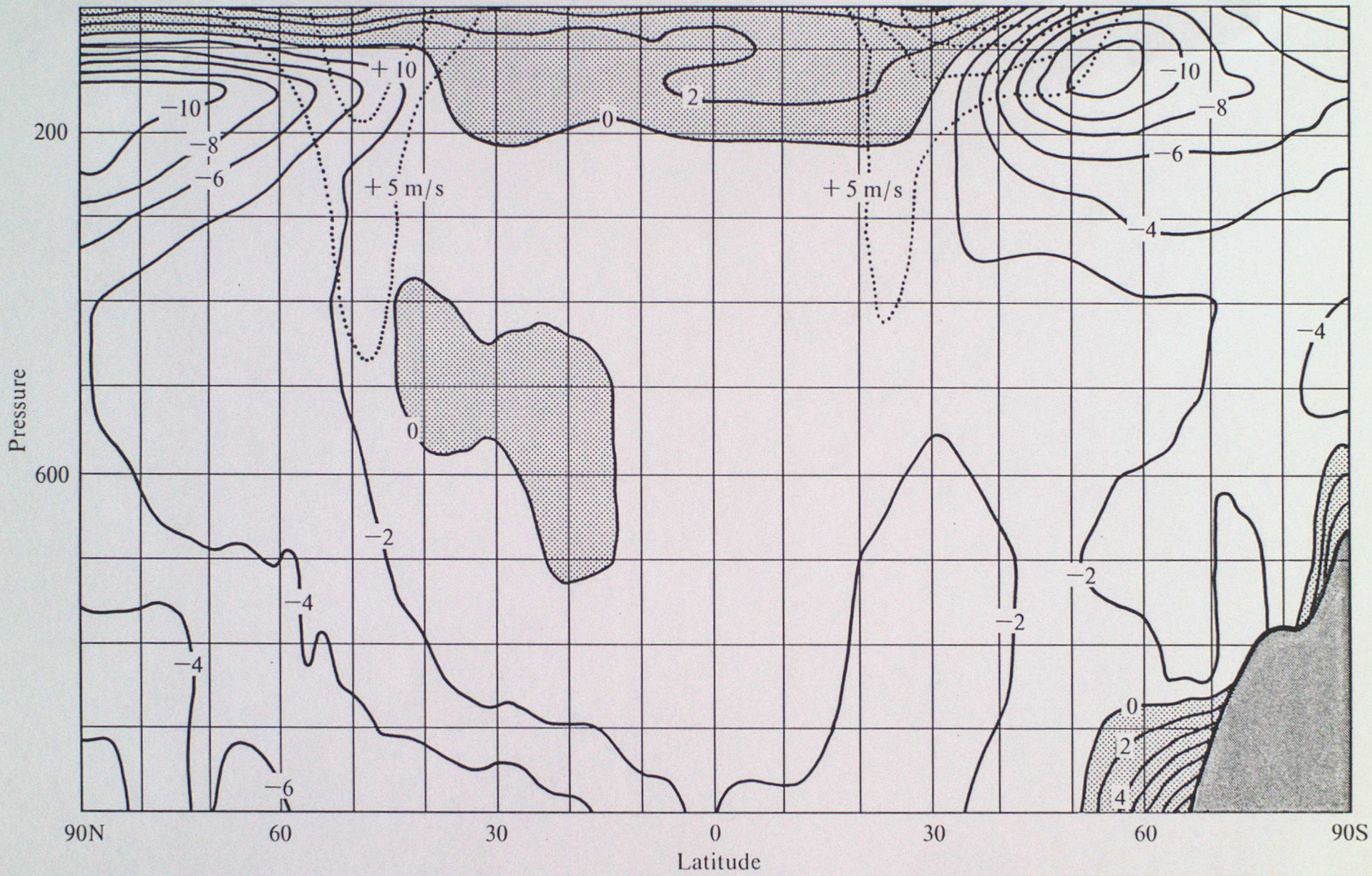


Figure 4: As Figure 3 except for June-August.

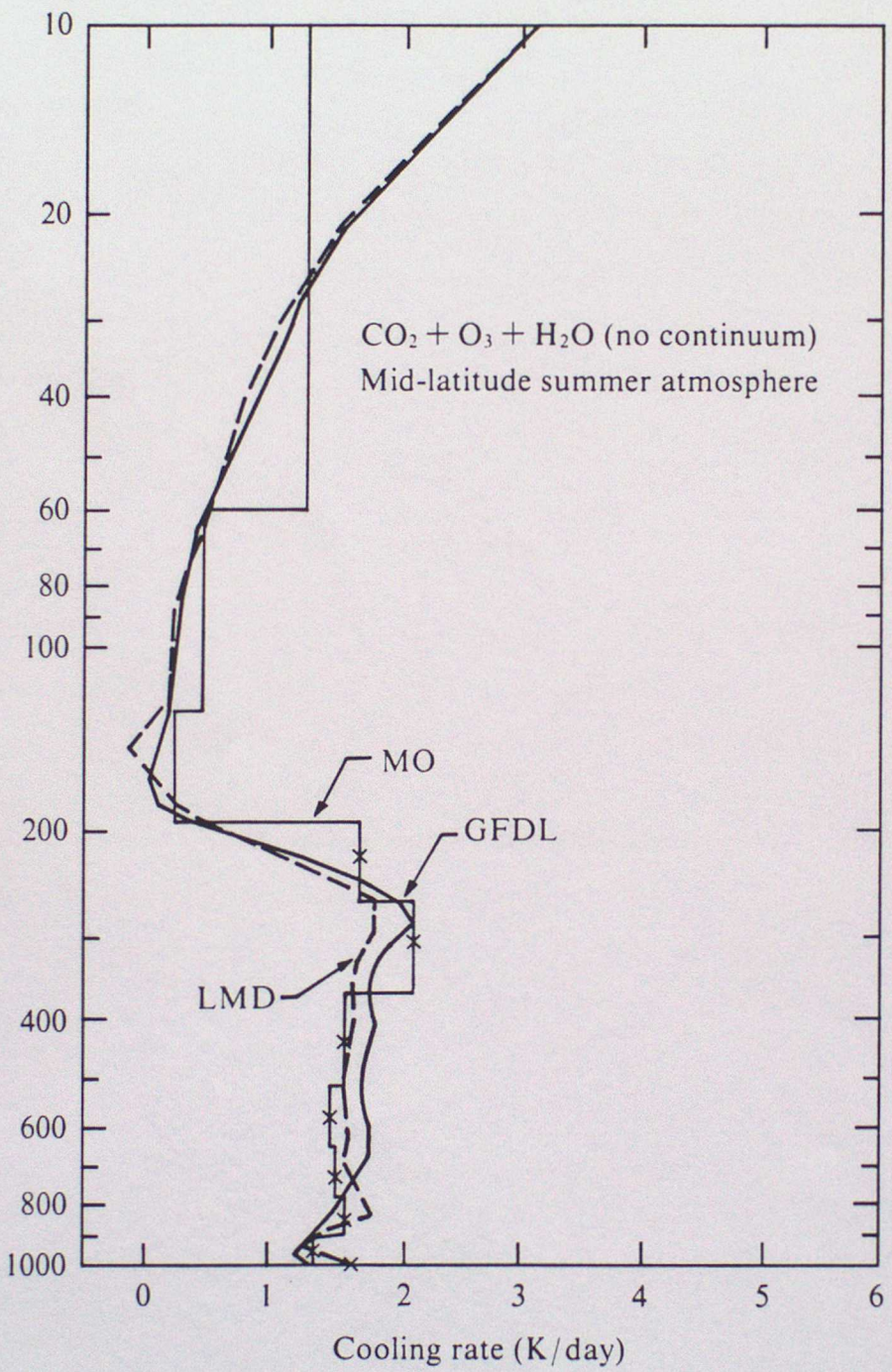


Figure 5: Longwave radiative cooling rates from line-by-line calculations with GFDL (solid curve) and LMD (dashed) schemes (Luther, 1984) and the MO GCM broadband scheme of Slingo and Wilderspin (1986) (A. Slingo, personal communication) (thin solid lines).

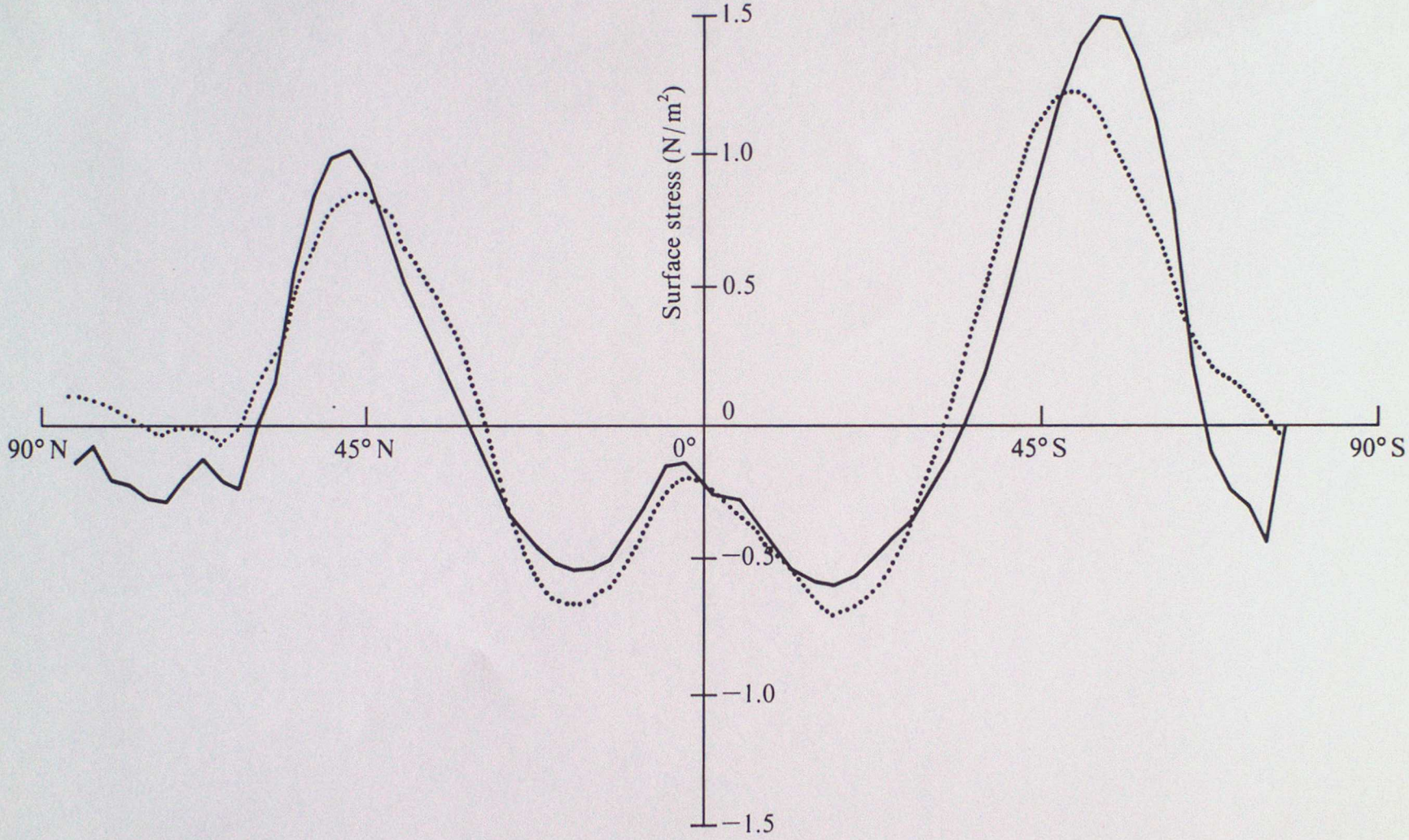


Figure 6: Zonally averaged annual mean zonal wind stress (sea only), observed (Hellerman and Rosenstein, 1983)) (dotted), and modelled (4 year mean for MO model) (solid).

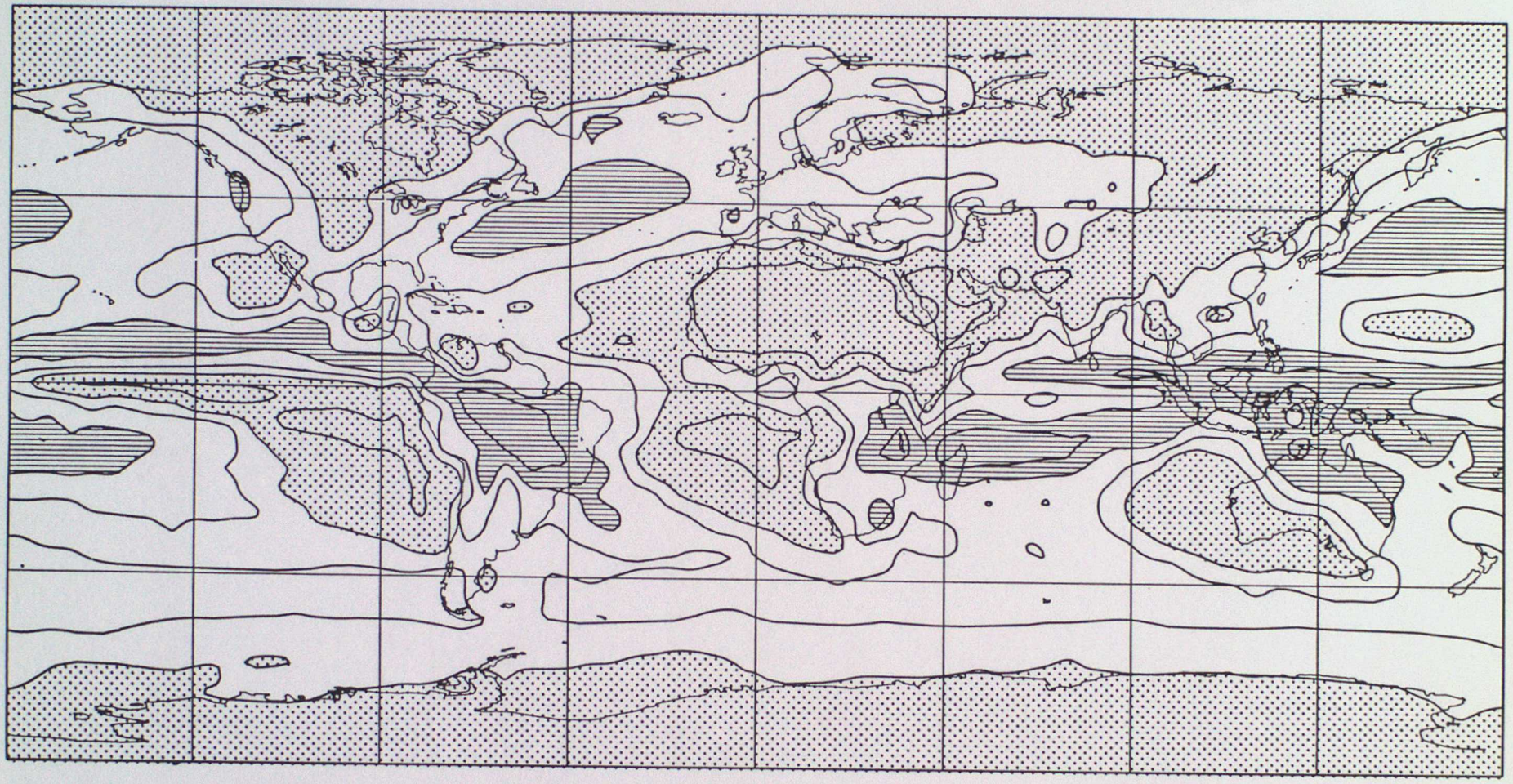


Fig. 7a

Figure 7: December-February precipitation (mm/day): (a) 4-year mean from MO model; (b) observed from Jaeger (1976).

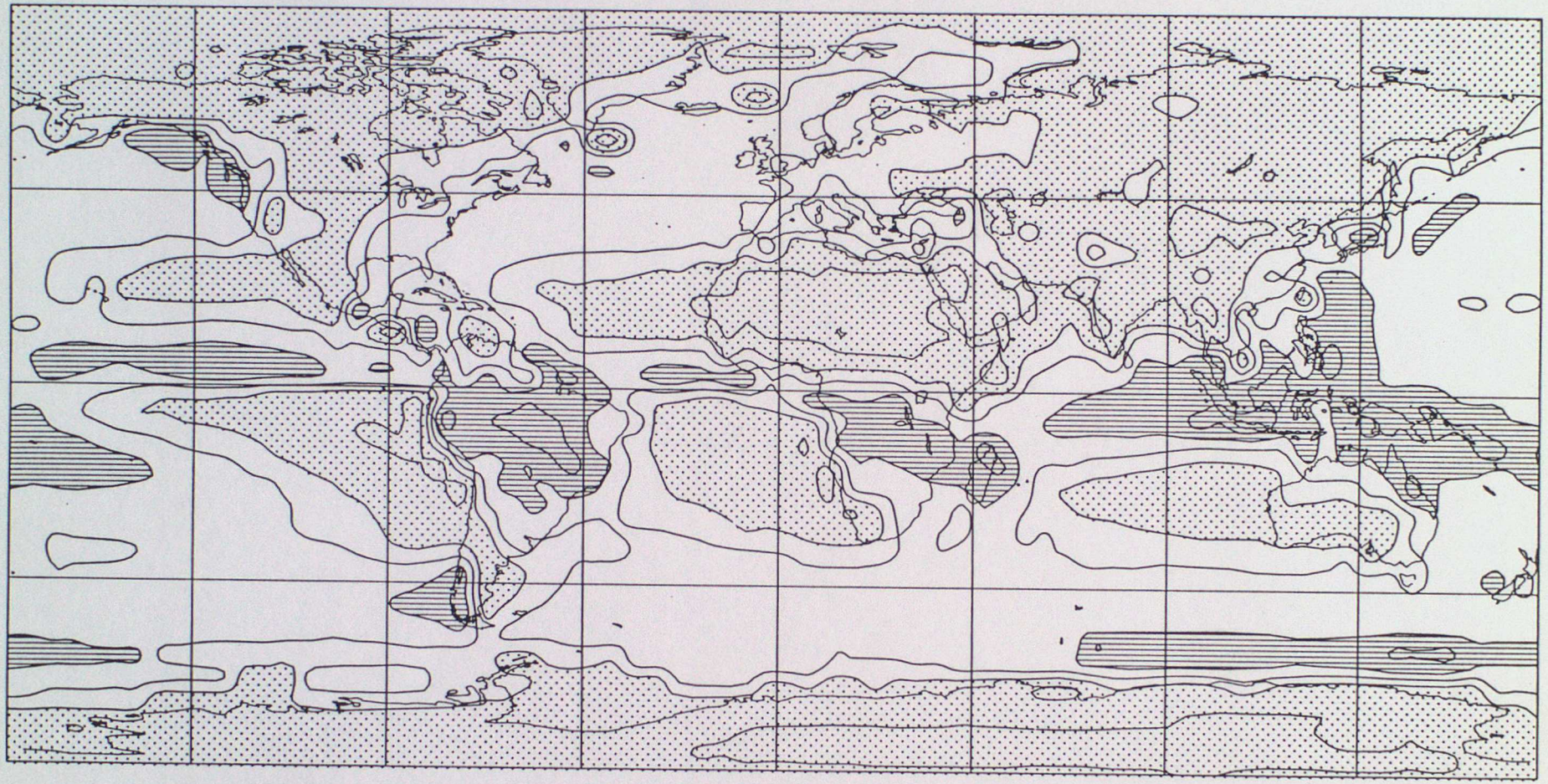


Fig. 7b

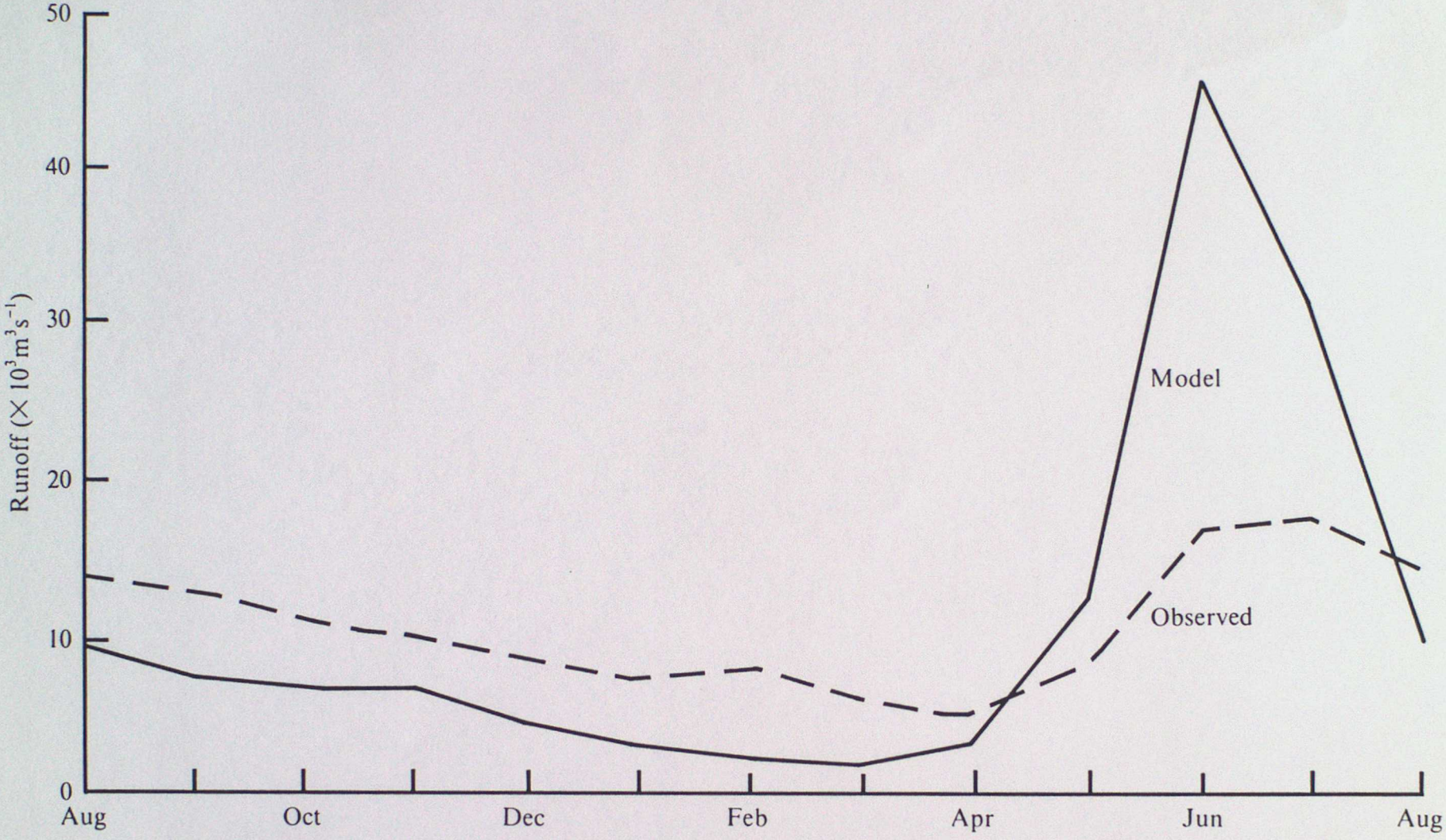


Figure 8: Modelled (solid) and observed (Mackay and Loken, 1974) (dashed) runoff for the Mackenzie basin ($10^3 m^3 s^{-1}$).

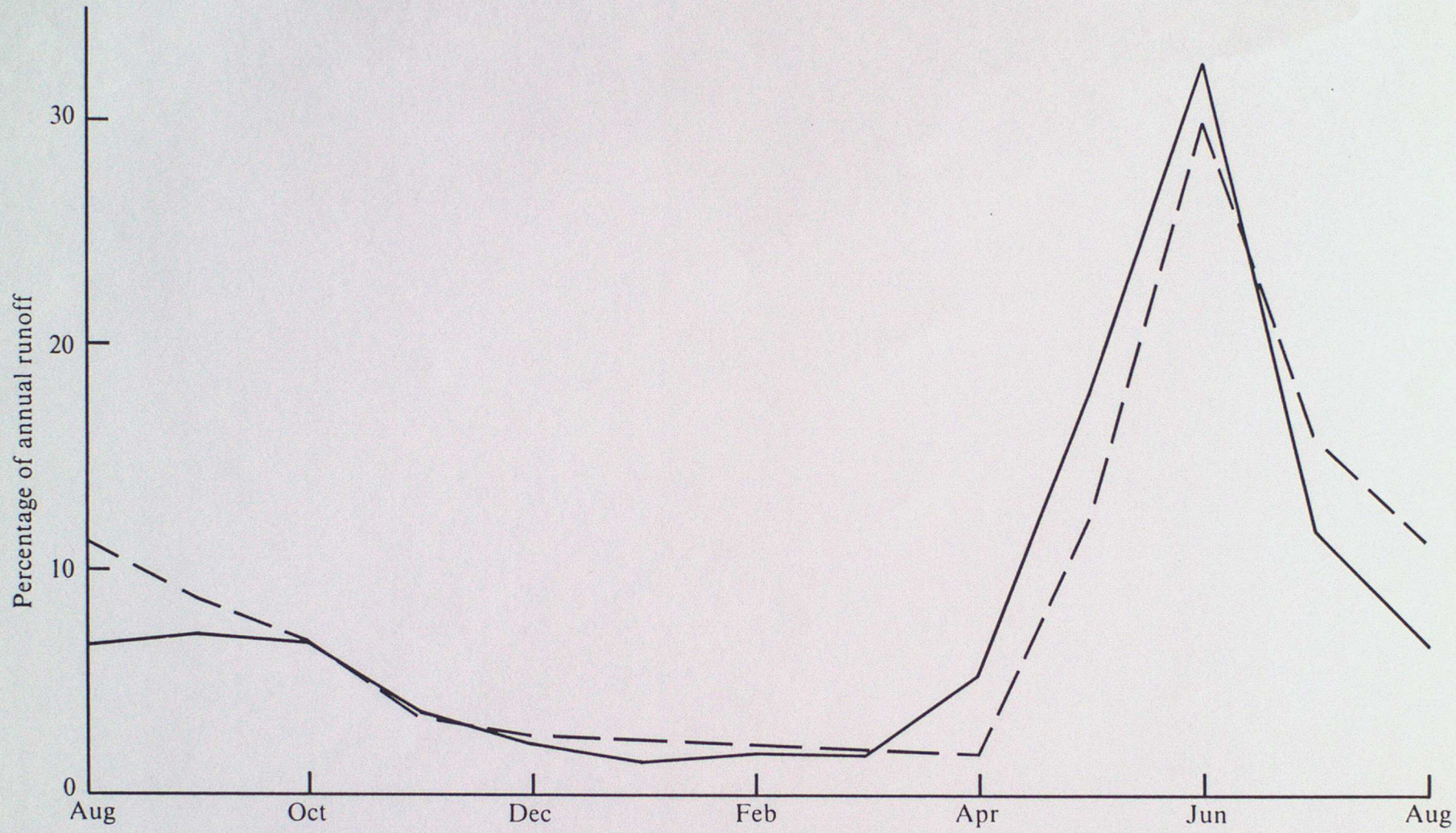


Figure 9: As Figure 8 but as percentage of annual total and for Ob'-Irtysh and Yenisei basins (observed) and 60-105 E north of 50 N (modelled).

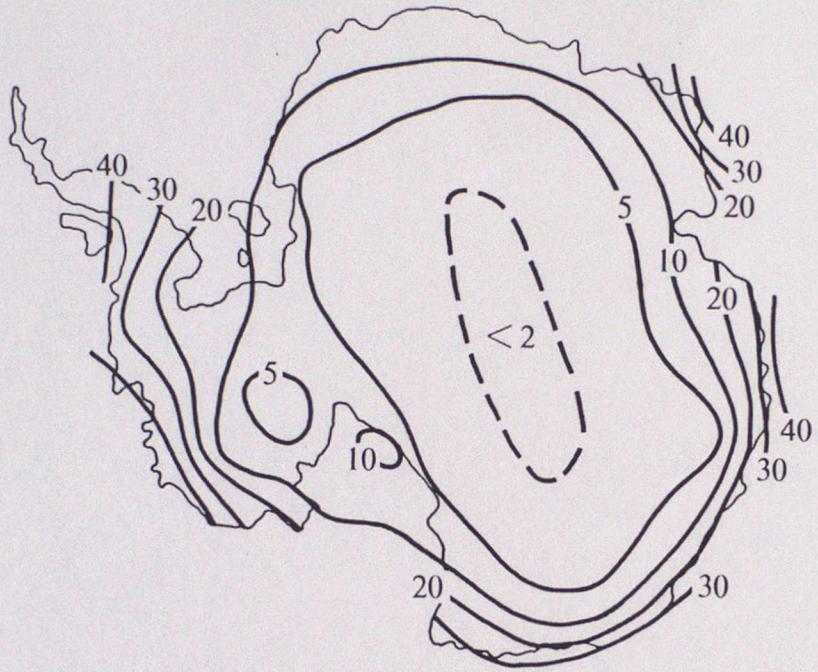


Fig. 10a

Figure 10: Annual snow accumulation (g/cm^2/yr) for Antarctica: (a) modelled from MO model; (b) observed according to Giovinetto from Schwerdfeger (1970)

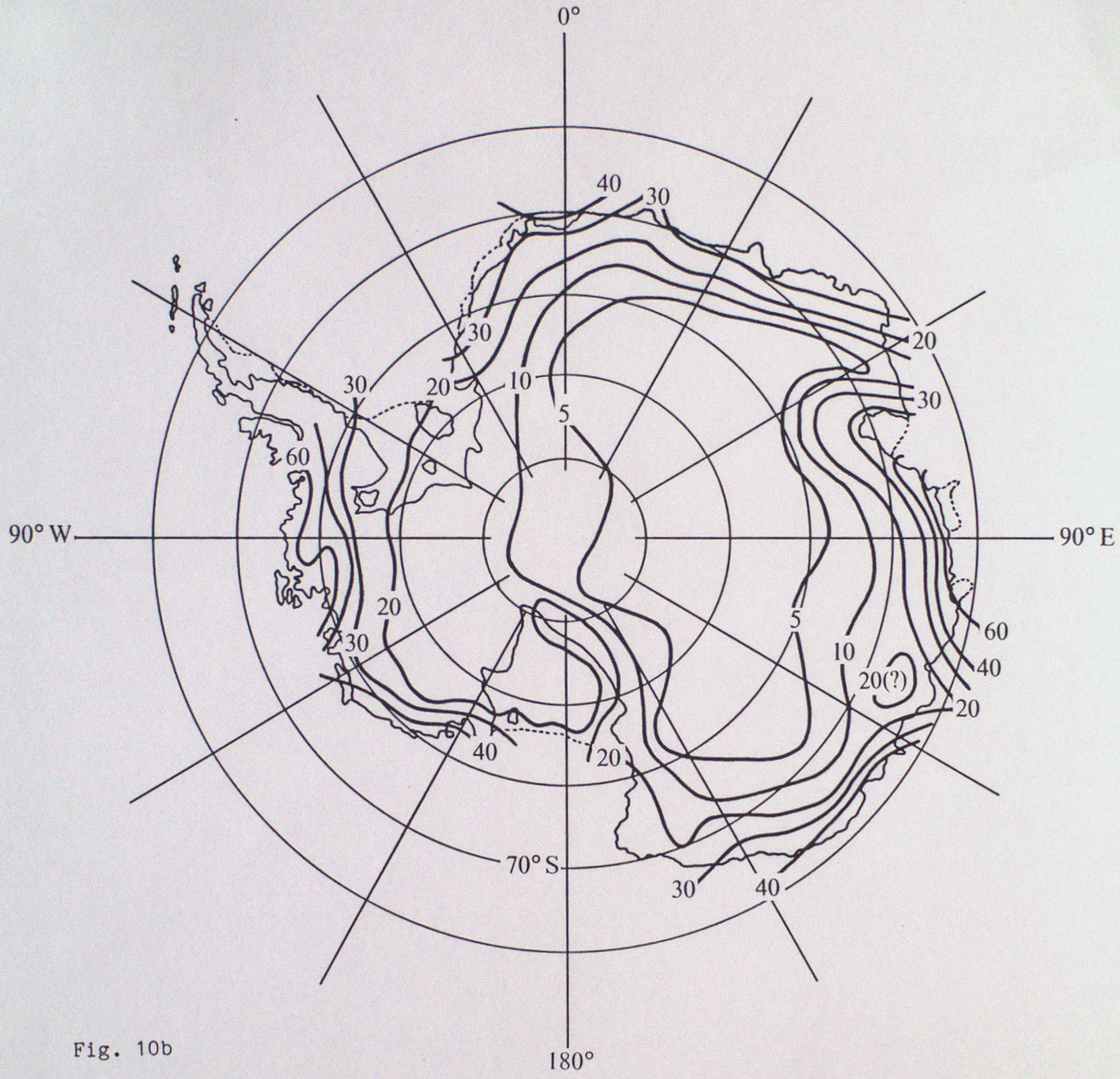


Fig. 10b

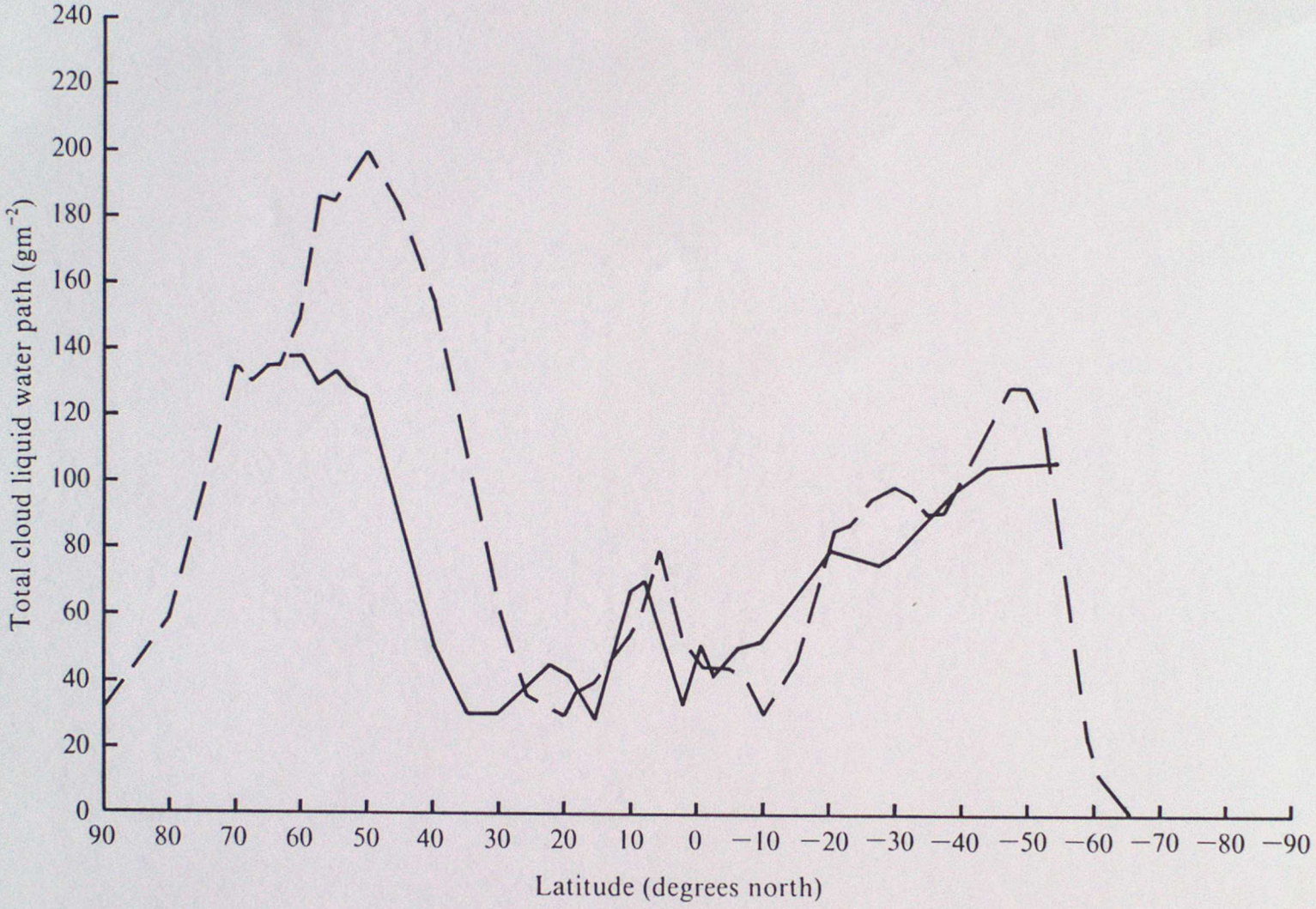
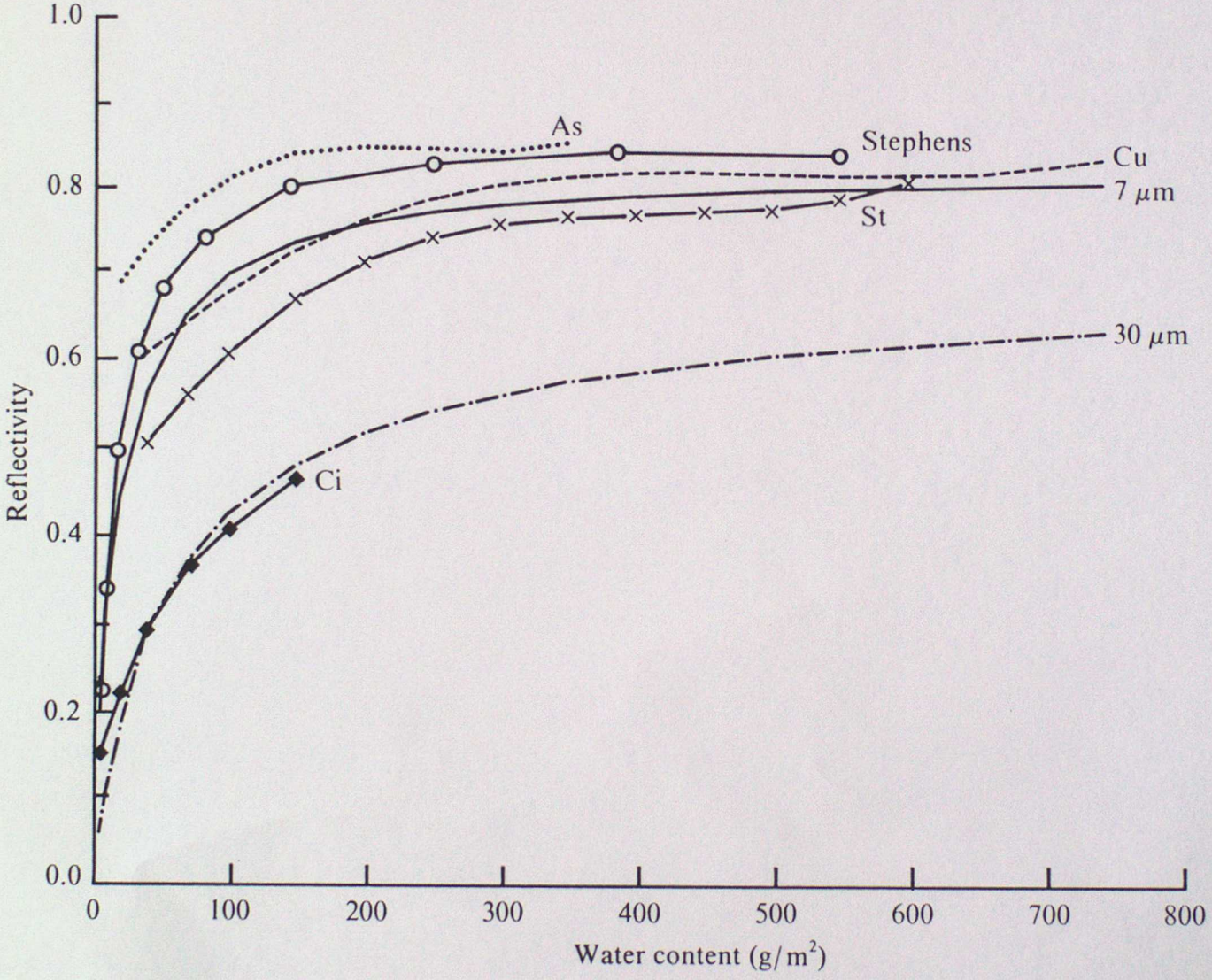


Figure 11: Zonally averaged cloud liquid water (g m^{-2}) as observed (ocean only) from Njoku and Swanson (1983) for July 11-August 10 1978 (solid) and modelled for June-August from MO model (all longitudes) (dashed).

Figure 12: Estimates of the relation between reflectivity and cloud water content for different clouds (stratus, cumulus, altostratus and cirrus from Liou and Wittman (1979), Charlock and Ramanathan (1985) 7 and 30μm effective drop radius and Stephens' (1984) spectral average.



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